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Article Follow up Control of a Second Order System in Sliding Mode Márk Domonkos* , Nándor Fink and Péter Korondi Department of Mechatronics, Optics and Mechanical

Engineering Informatics Faculty of Mechanical Engineering; Budapest University of Technology and Economics 4-6 Bertalan Lajos Street, 1111 Budapest, Hungary, e-mail: {domonkos, finknandor, korondi}@mogi.bme.hu * Correspondence: domonkos@mogi.bme.hu Version December 3, 2019 submitted to Energies 1 Abstract: The paper deals with instantaneous feedback controlled inverter using sliding mode 2 control. The theoretical contribution of this paper is that common state space based sliding surface 3 design method is extended for follow up control. Starting from the basic theory of sliding mode 4 control the shape of error signal trajectory is illustrated. The practical contribution of this paper is the 5 relationship between the shape of error signal trajectory and the Total Harmonic Distortion (THD) of 6 the output voltage signal. The conditions of sliding mode control in UPS is discussed. Rectifier as 7 non linear load is simulated. Experimentally validated simulation results are presented. 8 Keywords: sliding mode control; hysteresis control; second order system; UPS 9 1. Introduction 10 Power electronic equipment producing alternating voltage and current impulses is typical member 11 of Variable Structure Systems /VSS/. A VSS system usually has a state when it is insensitive to 12 parameter variations and load disturbances. This state is referred to as sliding mode. The cost of 13 insensitivity is the infinitely high switching frequency. Due to the switching delays and frequency limit 14 of controlled switches ideal sliding mode does not exist. In fact, there is an acceptable approximation 15 of ideal sliding mode. 16 The theory of variable structure system and sliding mode has been developed decades ago in 17 the Soviet Union. The theory was mainly developed by Vadim I. Utkin [1] and David K. Young [2]. 18 According to the theory sliding mode control should be robust, but experiments show that it has serious 19 limitations. The main problem by applying the sliding mode is the high frequency oscillation around 20 the sliding surface, the so-called chattering, which strongly reduces the control performance. Only few 21 could implement in practice the robust behavior predicted by the theory. Many have concluded that 22 the presence of chattering makes sliding mode control a good theory game, which is not applicable in 23 practice. In the next period the researchers invested most of their energy in chattering free applications, 24 developing numerous solutions like discrete time sliding mode [3], sector sliding mode [4], adaptive 25 sliding mode [5] terminal sliding mode [6]. 26 The design of a sliding-mode controller consists of three main steps. First is the design of the 27 sliding surface, the second step is the design the control law which holds the system trajectory on 28 the sliding surface, and the third and key step is the chattering-free implementation. The systematic 29 sliding manifold design for linear systems was proposed by Utkin [1]. This method was extended in 30 several way and optimal sliding manifold design were proposed, like frequency shaped sliding mode 31 [7], surface design based on H∞ control theory [8] and Tensor Product Model Transformation Based 32 Sliding Surface Design [9]. The reference signal was constant in the all previously mentioned papers. 33 The new element in this paper is that the original method was extended for Follow up Control. Submitted to Energies, pages 1 – 17 www.mdpi.com/journal/energies 34 According to [10] and [11]: Uninterruptable power supplies (UPS's) are being broadly adopted for 35 the protection of sensitive loads, like PCs, air traffic control system, and life care medical equipment, 36 etc., against line failures or other ac mains' perturbations. Ideally, an UPS should be able to deliver: 37 1) a sinusoidal output voltage with low total harmonic distortion during normal operation, even 38 when feeding nonlinear loads (particularly rectifier loads). 2) The voltage dip and the recovery time 39 due to step load change must be kept as small as possible, that is, fast dynamic response. 3) The 40 steady-state error between the sinusoidal reference and the load regulation must be zero. To achieve 41 these, the Proportional Integral (PI) controller is usually used [12], and robust stability and controller 42 robustness issues are discussed in [13]. However, when the system using PI controller under the case 43 of a variable load rather than the nominal ones, cannot obtain fast and stable output voltage response. 44 In the literature there can be found some hybrid solutions to overcome this problem [14][15]. The 45 principle of pulsewidth modulation (PWM) plays a very important role in power electronics [16]. In 46 the field of inverter technology, which produces sinusoidal voltage, a great number of "optimized 47 PWM" techniques have been proposed in the literature. These types of PWM inverters have very 48 good steady-state characteristics, but the voltage regulator response for sudden change in the load 49 takes a few cycles, and nonlinear loads can cause high "load harmonics". This is not acceptable in 50 Uninterruptable Power Supply (UPS) application for which instantaneous feedback is preferred [17] 51 [18]. Sliding mode control of power electronic inverters are suggested in [19] and [20]. The main 52 advantage of the sliding mode based method proposed in this paper is the direct control of the 53 transistor switches. The price that must be paid for is the uncontrolled THD. That is why the THD is in 54 the focus of this paper. 55 The structure of this paper is as follows. After the introduction, the Section 2 presents the problem 56 statement. Describes the system configuration and summarizes the sliding mode control design. The 57 Section 3 describes the system equations, shows how to apply the mathematical foundations on a 58 practical example. Follow the main steps of sliding mode design, namely the surface design, the 59 selection of control law considering the reduced chattering. The Section 4 presents simulation results, 60 which is validated by experimental measurement of a 10 kVA uninterruptable power supply (UPS).

61 Finally Section 5 the concludes the presented results. 62 2. Problem Statement 63 2.1. System Configuration 64 A simplified diagram of the inverter and the filter is shown in Fig.1. Vb is the battery voltage. vi is 65 the input voltage of the system, which is a filter with load. The input signal has three different values 66 (Vb,−Vb, and 0) depending on the switching states of the transistors. The goal is that the transistors 67 must be switched in such a way that vo, the output voltage of the system follows the sinusoidal 68 reference signal. The Ls in Fig. 1 is the leakage inductance of the transformer, which has a special 69 structure to increase and set the value of Ls. The main field inductance Lp cannot be ignored from the 70 point of view of the resonant circuit. The transformer loss is modelled by an increased load. 71 72 vo(t) = 2·230cos(2π50t) √ 2.2. Sliding Mode Control A SISO system is given in state space controllable canonical form. ẋ(t) = Ax(t) + bu(t) y(t) = cx(t) (1) (2) (3) Figure 1. Simplified figure of the inverter and filter 73 where x(t) ∊ Rn, A ∊ Rn×n, b ∊ Rn×1, c ∊ R1×n and u(t), y(t) ∊ R. y(t), the output variable of 74 the controlled plant, can be described by n-th order differential equation and let us suppose that yr(t) 75 is the reference signal, can be differentiated at least n times. 76 The goal is given in (4). 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 yr (t) = y(t) if t> Tc where Tc is the is the control period. The system error, ey(t) given in (5) . ey(t) = yr(t) − y(t) (4) (5) Thus the error signal, ey(t) can also be differentiated at least n times, so the n − 1-th derivative must exist and it is continuous. Due to the latter property, when trying to eliminate the error, it is also useful to control its derivatives (including the n − 1-th derivative). Otherwise, because of the system inertia, oscillation with large amplitude could arise. The essence of sliding mode could be summarized as follows: In order to eliminate the error in the n-th dimensional phase space a continuous error trajectory running into the origin is designed. The physical limits should be taken into account in the course of planning. After a transient designed by us the ideal system follows the reference signal without any error. The control signal is designed so that the trajectory realized does not deviate from the prescribed one or having reached the origin it remains at rest. Usually, σ, a scalar variable can be defined which can be considered as a positive or negative distance between the desired and actual trajectory, or each trajectory sector can be prescribe by a single scalar variable. The controllers task is to keep this scalar variable zero. In classical method of sliding mode control this scalar variable is calculated as a linear combination of the error and its derivatives [1]. Let us define the scalar variable, in case of n = 2, by the following equation: σ (t) = ey (t) + τėy (t) where τ is a time constant type control parameter chosen by us. In sliding mode σ = 0 and the trajectory is described by the following equation: ey(t) = −τėy(t) (6) (7) (8) (8) corresponds to a −1/τ slope line in the phase plane. This is usually referred to as sliding line or sliding surface in multi dimension phase space. The solution of equation (8) is an exponential function with negative exponent. ey(t) = E0e−τt t ≥ 0 (9) 97 where E0 = ey(0). Consequently, the error will decrease according to the chosen time constant τ, 98 independently from the system parameters (for instance load). After exponential transient process 99 yr(t) = y(t). To ensure that the system move in all cases towards sliding mode (i.e. towards σ(t) = 0) 100 the following condition is necessary: σ (t) σ ˙(t) ≤ 0 (10) 101 The design of sliding mode controller does not require accurate modelling: it is sufficient to know 102 only the bounds of the model parameters and the disturbance. During sliding mode the only task is to 103 switch the control signal so that (10) be valid in every instant. No other information is needed of the 104 controlled plant and the disturbances. It is enough to determine whether (10) holds or not. In simple 105 cases (or within a range of error and its derivatives) the sign of the control signal and that of σ˙(t) is 106 opposite. Thus it is often enough to use a relay controller, which switches control signal according to 107 the sign of parameter σ(t). 108 2.3. Follow-up Control 109 Since yr(t) is not constant Wyr,u(s) the transfer function from u(t) (vi(t)) to yr(t) (vo(t)) must be 110 calculated. According to (4), it is the inverse of the inverted system transfer function 111 112 113 114 115 116 117 118 y(s) = Wu,y(s)u(s) Wyr,u(s) = Wu−,y1(s) Usually, the inverse of Wu, y(s) cannot be realized. In our case, yr(t) is sinusoidal yr(t) = 2Vr cos (ωrt) √ (11) (12) (13) Only two parameters must be calculated. The gain (Gr) and phase shift (ϕr) of the system transfer function at the reference angular frequency (ωr). The definition of the error (5) must be modified. √ ey(t) = Vr cos (ωrt − ϕr) − y(t) 2 (14) Gr 3. System Equations 3.1. Filter and Load Using the notation of Fig. 1, the equation for the currents ii(t) = io(t) + ip(t) + ic(t) (15) Assuming resistive RL load io(t) = vo(t) 1 (16) RL The input voltage equation vi(t) = Ls dii(t) + vo(t) (17) dt 119 Substituting (15) and (16) into (17) , the filter circuit with resistive load can be described by the 120 following differential equation vi (t) = LsCpv¨o (t) + Ls 1 RL v˙o(t) + vo(t) G (18) 121 where G = Ls + Lp Lp (19) 122 The the transfer function from u(t) (vi(t)) to yr(t) (vo(t)) (including the effect of resistive load) 123 can be calculated from the Laplace transformed form of (18) vo(s) = G GLsCps2 + RLs s + 1 GL vi(s) = W(s)vi(s) (20) 124 3.2. The states of state space equation 125 Since the inverter and the load is handled separately the system has two inputs ui and io. Since 126 the input current must be calculated three state variable are selected for the three storage elements, 127 even if they are not independent and the rank of the system matrix is only 2. Using the notation of Fig. 128 1, the three state variable are ii(t), ip(t) and vc(t). ii (t)) x(t) = ⎢ip(t))⎥ (21) ⎢ vo(t) ⎥ 129 The load is connected parallel to the inverter capacitor Cp. The load current

includes the effect of ⌊ ⌋ 130 the transformer loss. The system has three outputs since vo(t) = vc(t) and its derivative are necessary 131 to calculate the scalar variable and ii(t) is visualised. In the real system, the capacitor current is 132 measured instead of v˙o(t). 133 According to (15, (16) and (17) the system matrices: 0 0 − L1s 0 1 − L1s 1 0 0 0 0 A = ⌈ 0 0 Lp 1 (22) 1 − C1p ⌉ B = ⌈ 0 0 ⌉ C = ⌈0 0⌉ D = ⌈0 0⌉⌉ Cp 0 ⌉⌉ − C1p 0 ⌉ 0 0 1 0 0 ⌊ ⌋⌊ ⌋⌊ ⌊ ⌋⌋⌊ ⌊ ⌋⌋ 134 3.3. Error Trajectory 135 To calculate the error defined by (14), Gr and ϕr must be calculated first. According to (20) , 136 W(jωr) = GLsCp(jωr)2 + GRLLs jωr + 1 G Gr and ϕr can be calculated from (23), where W(jωr) is a simple complex number. (23) Gr = |W(jωr)| (24) ϕr = angle(W(jωr)) (25) 137 Since the filter must be inductive, the sign of ϕr must be negative. It means, the reference signal 138 must lead to vo(t), which is the controlled signal in (14) y(t) = vo(t) (26) 139 The derivative of the error: 140 √ ėy(t) = −ωr Vr sin (ωrt − ϕr) − v˙o(t) 2 Gr The scalar variable of sliding mode is calculated by (6). (27) 141 3.4. Control Law 142 Three different control laws are examined. All of them can control directly the switching of the 143 transistors. This is the main advantage of sliding mode control in field of power electronics. More 144 advanced controller can be found in [21]. 145 146 147 148 149 150 151 152 153 154 155 156 157 158 159 160 3.4.1. Simple Relay The input voltage on the filter is switched according to the sign of σ(t). vi(t) = Vbsign(σ(t)) The main problems of (28) from practical point of view are • the inverter has zero state, which is not applied • the switching frequency is not controlled. 3.4.2. Double Relay The solution for the first problem is the usage of two relays. vi(t) = Vb sign(σ(t)) + Vb sign(cos (ωrt − ϕr)) 2 2 (28) (29) Vb and 0 are switched in the positive half period. −Vb and 0 are switched in the negative half period. But (29) does not solve the second problem. 3.4.3. Dead-zone-hysteresis Double Relay Both problems can be solved a dead-zone-hysteresis double relay. This control law is shown in Fig. 2. Figure 2. Dead-zone-hysteresis relay 3.5. Stability Analysis Using a simple relay controller, it is checked whether (10) holds or not. σ˙(t) must be expressed first σ˙(t) = ėy(t) + τëy(t) (30) According to (27) √ ëy(t) = −ωr2 Gr 2 Vr cos (ωrt − ϕr) − v¨o(t) (31) 161 v¨o(t) can be expressed from (18) v¨o(t) = 1 vi(t) − 1 v˙o(t) − 1 (32) LsCp RLCp GLsCp vo (t) 162 Substituting (28) into (32) v ¨o(t) = Vbsign (σ(t)) − v˙o(t) vo (t) RLCp GLsCp − (33) LsCp 163 According to (30) and (31) if the value of v¨o(t) is big enough and the system operates in an area, 164 which is close enough to sliding mode than the sign of v¨o(t) is opposite that of σ˙(t). It is clear from (33) 165 if the value of Vb is big enough and the system operates in an area, which is close enough to sliding 166 mode than the sign of v¨o(t) is same that of σ(t). As a conclusion, if the value of Vb is big enough and 167 the system operates in an area, which is close enough to sliding mode than the sign of σ(t) is opposite 168 that of σ˙(t). Similar analysis can be done for all control laws. In the practical cases substituting the 169 actual parameters of the system all examined control laws fulfill the condition (10) in the normal 170 operation area. The simulations proved this statement. 171 4. Simulation 172 MATLAB-Simulink simulations were carried out. 173 4.1. MATLAB-Simulink model 174 The main elements of the MATLAB-Simulink model are shown in Fig.3, Fig.4, Fig.5 and Fig.6. 175 Even if the structure of the controller shown in Fig.6 is quite simple, its performance is quite robust. Figure 3. The whole system Figure 4. Subsystem for calculation of scalar variable. Figure 5. Subsystem for the load. Figure 6. Subsystem for dead-zone-hysteresis relay controller 176 4.2. Model validation 177 The simulation results are compared to old measurement results of [22] shown in Fig.7. The 178 nominal power of the inverter is 10 VA. All parameters of (14) and (22) in addition the values of dead 179 zone and hysteresis shown in Fig.2 are known from [22]. 180 Like in case of the real system, where the σ was tuned manually to set the number of switches per 181 period, σ is changed to achieve similar result in the simulation as in the real system. The simulation 182 result is shown in Fig.8 after setting the value of σ. Figure 7. Reference measurement result Figure 8. Reference simulation result 183 The first faced problem in the simulation is the steady state. In case of the measurement of the 184 real system, the screen of the oscilloscope seemed to be frozen in most settings of σ. It means that the 185 error trajectory is a closed curve in a period in steady state. 186 Using the default settings of Simulink, a quasi steady state period of the error trajectory of 187 simulation are shown in Fig.9. The consequent periods are slightly different, that causes subharmonics, 188 which is crucial from the practical point of view. 189 The main question is that whether this subharmonics are the immanent property of the applied 190 switching method or result of the insufficient precision of the simulation. After caring out numbers 191 of simulation with different model configuration parameters of Simulink. It is concluded that the 192 precise calculation of switching instant is the key point of simulation of proper steady state. The 193 Ode113(Adam) method is most suitable integral method for switching systems. (The equation solvers 194 for UPS are compared in [23]). 195 4.3. Analysis of the simulation results The main advantage of PWM technique is that the filter can be smaller that results smaller no-load current. The parameters of the filter is given in (34). The value of the nominal load is RL = 5.3Ω. Ls = 3.5mH, Lp = 32mH, Cp = 320μF (34) Figure 9. Error trajectory in a quasi steady state period 196 τ, the slope of switching line of sliding mode is changed. The relationship between the slope of 197 switching line and the number of switches is shown in Fig.10. The bigger the value of τ the smaller the 198 slope of the switching line and the bigger the number of switches per period. On the other hand the 199 bigger the value of τ means longer transient according to (9). The optimum must be calculated. Figure 10. The effect of τ on the number of switches 200 The number of switches per period and the total harmonic distortion (THD) are shown in Fig. 11 201 as a function of τ. The first one is staggered. The bigger of number of switches are the bigger of 202 switching loss and the smaller the THD are. The optimum is around 52 switches. It means 13 pulses 203 per period like in Fig.7 and in Fig.8. The step of the optimal switching number is magnified in Fig.12. Figure 11. Number of switches and THD Figure 12. The optimal number of switches and its THD 204 There is a local minimum of THD in the middle of a stair (in Fig.12) when the transient between 205 the positive and negative half periods are smooth as shown in Fig.13. Figure 13. Smooth transient of error trajectory 206 By increasing τ, the transients are changing slightly. First a V shape appears (see in Fig.14). 207 By increasing τ further, the V shape transforms to a loop (see in Fig.15) and the last pulses in all 208 half periods have opposite sign than that of the reference signal (see in Fig. 16) that increases the THD. 209 Finally, the number of switches per period is increased by 4 and the transients have V and loop forms 210 again (see in Fig.17), which disappears in the middle of the stair. Figure 14. V shaped transient of error trajectory Figure 15. Loop shaped transient of error trajectory Figure 16. Control signal Figure 17. Transient of error trajectory after number of switches is increased 211 4.4. Nonlinear load 212 The most challenging load is the rectifier [24], since its current is not sinusoidal and it has a relative 213 big peak value. A rectifier like load is simulated, which has approximately same RMS current value as 214 that of the nominal current. The time-functions of the output voltage and current in addition the input 215 current are shown in Fig.18. The RMS value of the input no-load current is zero at the beginning of 216 the period, when the output current is zero. Since the load current is continuous and the reaction of 217 the sliding mode controller is practically instantaneous that is why this type of non linear load has no 218 significant effect on the output voltage, the THD is depends on the shape of the error trajectory, which 219 is shown in Fig.19. Figure 18. Output voltage, input and output current with rectifier like load Figure 19. Error trajectory of the non-linear rectifier like load 220 4.5. Switching on the load 221 Nominal resistive load is assumed and the load is switched on at the pick value of the output 222 voltage. The time-functions of the voltage and current is shown in Fig. 20. Since the current is 223 discontinuous there is a transient which is recognizable in the shape of the error trajectory in Fig.21. 224 The length of the transient depends on the the value of τ. It is 0.22 ms. The transient caused by any 225 step change of the load takes around 1 ms, which is really fast. Figure 20. Output voltage, input and output current after switching on the resistive load Figure 21. Error trajectory after switching on the resistive load 226 5. Conclusions 227 This paper introduced a follow up control method with sinusoidal reference signal for sliding 228 surface design and analyzed the performance of Dead-zone-hysteresis Double Relay controller 229 operating sliding mode. The simulation of variable structure systems is very sensitive to the integral 230 method of simulation. The zero crossing must be detected. Even if it is a relative simple controller, 231 which can be implemented by analogue operational amplifier it has very good performance with 232 nonlinear load as well. The positive and negative half periods can be separated by a dead- zone and 233 the switching frequency can be limited by hysteresis. The actual number of switches can be set by the 234 slope of sliding line. The value of the THD depends on the shape of the error phase-trajectory. The 235 non-linear load with continuous output current has no significant effect on the output voltage because 236 of the instantaneous behavior of sliding mode controller. 237 References 238 239 240 241 242 243 244 245

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